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Age-dependent sensitivity of trees disturbed by debris flows – Implications for dendrogeomorphic reconstructions

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A B S T R A C T

Dating of geomorphic events using dendrogeomorphic methods has increased rapidly during the last years to provide a systematic overview on event frequencies, spatial reach and magnitudes. Despite the recent advances in methodology, multiple questions remain when it comes to the age-dependent sensitivity of trees which may further influence the quality of dating. Yet, the impacts of ageing effects on dendrogeomorphic reconstructions have not been assessed in detail so far. This study clearly shows the evolution of numbers, types, and intensities of growth disturbances (GDs) across the lifespan of three different tree species (*Larix decidua* Mill., *Picea abies* (L.) Karst., and *Pinus sylvestris* L.) affected by debris flows in the European Alps. Based on the re-analyses of datasets from past dendrogeomorphic reconstructions and calculation of statistical tests we investigated decreased ability of all studied tree species to record the debris-flow impact with increasing age. The great abundance of GDs occurred between 31 and 60 year of a tree life. By contrast, below-average number of GDs started around the 10th decade. *L. decidua* and *P. abies* show almost twofold number of GD per tree and decade compared to *P. sylvestris*. Injuries and compression wood are the most frequent GDs at rather young ages of *L. decidua* and *P. abies* specimens while tangential rows of traumatic resin ducts and abrupt growth increases are much more scattered. The most balanced distribution of GD is obvious across the lifespan of *P.sylvestris*. Unequivocal signals (GD of intensity reactions: 5, 4, and 3) of all tree species occur at significantly younger ages than uncertain signals of debris flow impacts (GD of intensity reactions: 2, 1, and 0). Based on the findings of this study and with the aim of improving detection of debris flows we proposed options of sampling strategy and laboratory steps (namely identification of an event) for forest stands with different age structure. Whereas the study sites across the world may not provide the “ideal” age composition of forests due to, for instance, forest management interventions or presence of high-magnitude disasters, the list of recommendations provided here seems to be a good alternative when the conditions are somewhat limited.

1. Introduction

Interactions between vegetation and hillslopes – including the protective functions of forest – are among the most critical issues in regions affected by natural hazards, and of key importance when it comes to services provided by forest ecosystems (Swanston, 1974; Bugmann, 1994; Führer, 2000; Istanbulluoglu et al., 2004; Marston, 2010; Osterkamp et al., 2012; Stoffel and Wilford, 2012; Pawlik, 2013; Temgoua et al., 2016; Michelini et al., 2017). In temperate climate zones, trees also serve as silent witnesses of past geomorphic process activity and provide valuable information on event frequencies and spatial patterns of past process occurrences (Stoffel and Bollschweiler, 2009; Kaitna and Huebl, 2013). Dating of geomorphic events using tree-ring series is known as *dendrogeomorphology* (Alestalo, 1971) and allows dating of past events with annual or even up to seasonal accuracy (Stoffel et al., 2005a; Stoffel and Beniston, 2006). The approach has become a crucial tool for the creation of hazardous process histories in remote regions for which data is largely missing and other approaches cannot be used (Stoffel et al., 2010; Ballesteros-Cánovas et al., 2015).

Debris flows are manifested in mountain environments where

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they can considerably devastate infrastructure and human settlements (Jakob and Hungr, 2005; Borga et al., 2014). Trees growing along debris flow paths or on accumulation fans can record mechanical disturbance of debris-flow surges through the formation of distinct growth disturbances (referred to as GDs hereafter) in their tree-ring series (i.e., scar with formation of callus tissue, onset of reaction wood with eccentric growth, abrupt growth suppressions and increases, and the presence of tangential rows of traumatic resin ducts (TRD) in some conifers; Bollschweiler and Stoffel, 2010a; Stoffel and Corona, 2014 and references therein). To quantify debris-flow activity at a site and to differentiate geomorphic signal from noise, several dendrogeomorphic approaches have been used in the past. Early quantitative approaches (based on dendrogeomorphic indices) primarily took account of the ratio between the number of disturbed trees with respect to the number of sampled trees living at a specific moment in the past (Shroder, 1978). To render analysis more robust, weighting factors and indices have been introduced more recently to classify GDs according to their intensity (Ruiz-Villanueva et al., 2010; Kogelnig-Mayer et al., 2011; Schneuwly-Bollschweiler et al., 2013; Tichavský and Šilhán, 2015). In addition, event detection also included the position of trees disturbed by the same event (i.e. semi-quantitative and/or expert approaches; Bollschweiler et al., 2007; Tichavský et al., 2017). Finally, Stoffel and Corona (2014) proposed a list with all types of GDs and the intensities of reactions to be included in future dendrogeomorphic research, with the idea to avoid fragmentation of criteria defining an event.

Despite these recent advances, multiple questions remain, notably with respect to the quality of dating and the assumed age-dependent sensitivity of trees and forest stands to record events. In this sense, different age-dependent sensitivities may have an impact on the nature and the character of growth responses in trees as a result of changing age and stress conditions. From an ecological perspective, trees change their growth rate with time and as a result of changing physiological conditions, changing anatomy and environment (a phenomenon called senescence; Fritts, 1976). In a similar way, changes in the percentage of sapwood and heartwood as well as the proportion of latewood across a tree's lifespan will further influence its strength, specific gravity, and the efficiency of water and nutrient translocation mechanisms (Kozlowski, 1971). Young trees are generally more sensitive to temperature and light variations, whereas old trees are more likely to suffer from insect attacks and fungi diseases, which results in worsened vitality (Kozlowski, 1971; Vaganov et al., 2006). Stress conditions can be age-dependent as well, for example due to the reduction in the efficiency of water and nutrient translocation mechanisms (Szeicz and MacDonald, 1994). In contrast, several authors state that trees growing under optimal ecological conditions would not reach as high ages as stressed individuals (Schulman, 1958; Schweingruber, 2007). In this context, Fritts (1976) highlights that growth changes associated with increasing age may vary from site to site.

From a geomorphic perspective, Šilhán and Stoffel (2015) pointed out that trees characterized by juvenile growth are considered more sensitive to geomorphic processes, but that they would also be more sensitive to other, non-geomorphic disturbances (e.g., ungulate browsing, snow pressure, internal stands dynamic, etc.). Trappmann et al. (2013) mentioned the effect of bark thickening as well as the reducing of tree vigour in older trees as being potentially responsible for the decreasing sensitivity of older trees to geomorphic processes. In the study of Šilhán (2016) realized in Central Europe, the highest sensitivity of Norway spruce to stem tilting due to landslide movements occurred during the 8th and 9th decade of tree age. In another assessment Tichavský and Šilhán (2016) confirmed that younger (up to 60 years old) and thinner (up to 25 cm in diameter) individuals of Norway spruce are more sensitive recorders of hydrogeomorphic processes than older trees.

Yet, the impact of ageing effects on dendrogeomorphic reconstructions has not been assessed in detail so far. This lack of quantitative data on tree sensitivity leads to several research questions, which we are going to address by using trees affected by debris flows in the European Alps: When are trees most sensitive to debris-flow impacts? Are older trees able to record debris flows in the same way as younger ones? Are there any differences in the intensity and/or type of GDs recorded by trees across their lifespan? And can we observe similar “age-dependent trends in sensitivity” in different tree species?

To thoroughly understand the changing ability of trees to record geomorphic processes, we analysed GDs of three different tree species which are commonly used for dendrogeomorphic reconstructions of debris flows: European larch (*Larix decidua* Mill.), Norway spruce (*Picea abies* (L.) Karst.), and Scots pine (*Pinus sylvestris* L.). Our goals were (i) to reveal how the number of GDs per tree changes with tree age (given in decades), (ii) to reveal how the ratio of particular GD types and intensity categories develop across the lifespan of a tree, and (iii) to verify age-dependent reactions in trees to high-magnitude debris flow at several study sites in the European Alps. The overall goal of this study, based on the synthesis of these goals, thus was to create recommendations on how to include tree sensitivity and age effects in future debris-flow reconstructions.

2. Material and methods

Our research is based on the re-analyses of increment cores sampled for the creation of debris-flow chronologies in the Swiss and Italian Alps (Fig. 1; Table 1). In the catchments analysed, debris flows typically originate above treeline and from environments which are (or have been) controlled by periglacial and glacial processes. Debris-flow events are triggered in these catchments as a result of rather localized, convective thunderstorms or longer-term, advective rainfall which occur at the study sites between spring and autumn (Schneuwly-Bollschweiler and Stoffel, 2012; Stoffel et al., 2011, 2014). In this study we focus on samples of *L. decidua*, *P. abies*, and *P. sylvestris* from thirteen debris-flow fans and channels (Fig. 1) in which the frequent occurrence of debris flows has been reconstructed previously (recurrence intervals at the individual sites fluctuated between 1 and 10 years in the past; Bollschweiler and Stoffel, 2010b).

Sampling and laboratory procedures followed the standard methodological approaches as described e.g. by Bräker (2002), Stoffel (2005), or Stoffel and Bollschweiler (2008). A minimum of two increment cores were extracted per tree during fieldwork (2001–2010). Tree-ring series from each core were counted and measured using a LINTAB measuring table and final curves were compared with appropriate reference chronologies from each site using the TSAP software (Rinntech, 2017). Finally, based on the visual inspection of samples and a comparison of the reference chronologies against the series from disturbed samples, the type and intensity of debris-flow induced GDs were identified.

The re-analysis of the datasets, presented in this study, consisted in (i) an identification and/or calculation of the age of the sampled tree, (ii) recording the tree age during which GDs occurred, as well as in (iii) summarizing and unifying types and intensities of GDs. The age of trees was determined as follows: For all increment cores, we searched for tree piths to obtain an idea of tree age at sampling height. In the case of missing pith, the number of missing rings was estimated by using a transparent sheet with concentric rings (Bosch and Gutiérrez, 1999). An age correction factor was then

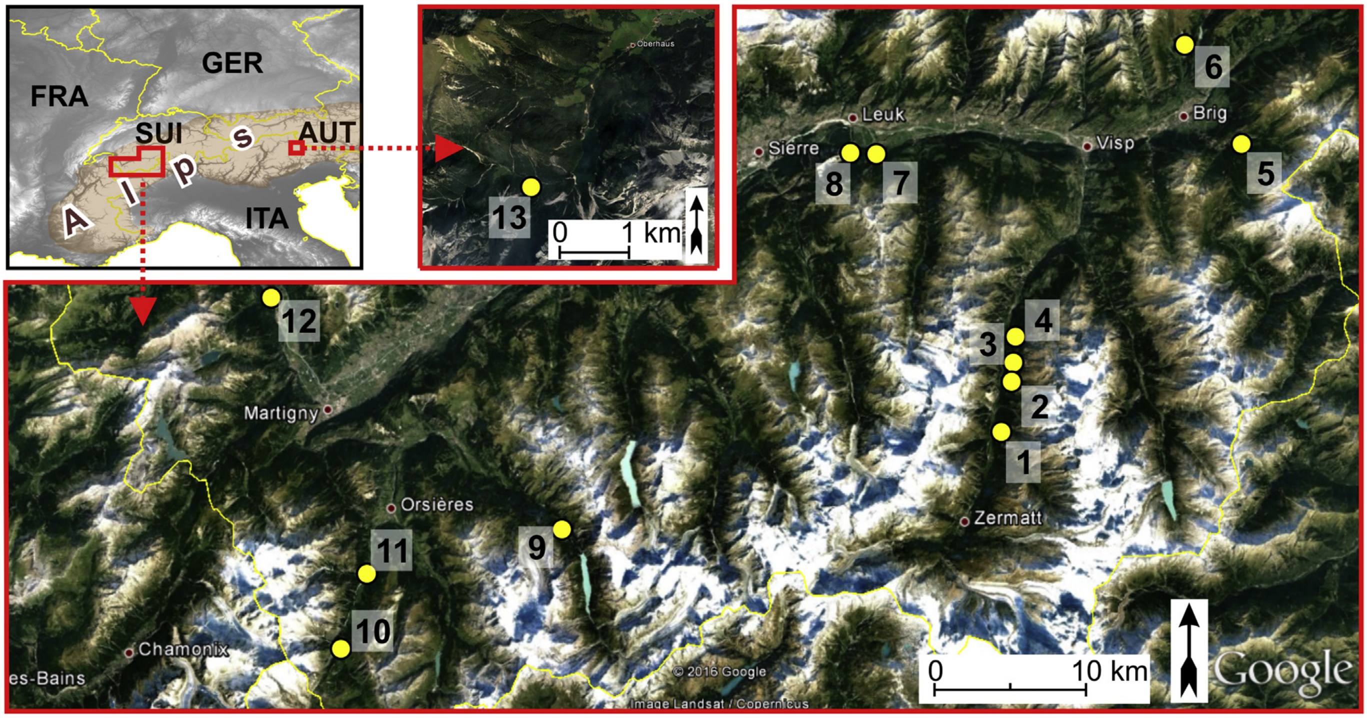

Fig. 1. Localization of the debris-flow torrents and fans in the Swiss and Italian Alps from which increment cores of disturbed trees were used for re-analysis: 1 – Wildibach, 2 – Fallzug, 3 – Bielzug, 4 – Grosse Grabe, 5 – Ganterbach, 6 – Bruchji, 7 – Meretschibach, 8 – Illgraben, 9 – Lourtiere, 10 – Torrent de la Fouly, 11 – Reuse de Saleinaz, 12 – Saint Barthélémy, 13 – Pragser Wildsee.

Table 1
Overview of the debris-flow sites selected for analysis and data sources.

ID information, Locality			Study site parameters			Results published in
ID	Locality	Country	Area (km^2)	Catchment elevation above the fan (m asl)	Debris flow fan elevation (m asl)	
1	Wildibach	SUI	8.3	4545–1540	1540–1420	Bollschweiler and Stoffel (2010b); Schneuwly-Bollschweiler et al. (2013)
2	Fallzug	SUI	1.9	3350–1420	1420–1250	Bollschweiler and Stoffel (2010b)
3	Bielzug	SUI	1.8	3192–1320	1320–1230	Bollschweiler and Stoffel (2010b)
4	Grosse Grabe	SUI	1.2	3178–1540	1540–1200	Bollschweiler et al. (2008a)
5	Ganterbach	SUI	36.2	3250–1100	without typical fan	unpublished
6	Bruchji	SUI	4.4	3230–1530	1530–1400	Bollschweiler et al. (2007)
7	Meretschibach	SUI	7.6	2960–880	880–660	Szymczak et al. (2010)
8	Illgraben	SUI	10.5	2720–880	880–610	Stoffel et al. (2008)
9	Lourtier	SUI	3.9	3220–1220	1220–1060	unpublished
10	Torrent de la Fouly	SUI	1.0	2820–1760	1760–1520	Bollschweiler and Stoffel (2007)
11	Reuse de Saleinaz	SUI	23.0	3900–1400	1400–1150	Bollschweiler and Stoffel (2007)
12	Saint Barthélémy	SUI	12.0	3180–600	600–440	unpublished
13	Pragser Wildsee	ITA	0.3	2180–1650	1650–1510	unpublished

applied to compensate for the time a tree takes to grow from germination level to sampling height (McCarthy et al., 1991). Based on height-age models, which assume that apical growth is equally proportioned within a sampled section (Carmean, 1972), we divided tree height by the number of tree rings to obtain an average rate of yearly apical increment for each tree. The sampling height was then divided by the yearly increment to obtain the number of missing rings (Bollschweiler et al., 2008a). Absolute tree age was then used to determine the age at which GDs occurred in the tree-ring series. In the case of scars and TRDs, the particular year in which they occur was noted; in the case of reaction wood and abrupt growth suppressions and increases, the particular year of GD onset was noted (Tichavský and Šilhán, 2016).

In a next analytical step, we checked the distribution of all GDs across the lifespan of each tree and for the different tree species so as to obtain the mean number of different GD per tree for the different decades of its life. We excluded GDs occurring in the first decade as juvenile wood is prone to record many non-geomorphic signals, such as increased production of TRDs (Larson, 1994; Stoffel et al., 2005b) or the onset of compression wood due to pressure exerted by snow, neighbouring trees, or animals (Šilhán and Stoffel, 2015). Analysis was restricted to only those age intervals for which the number of examined trees exceeded 100 individuals. The mean number of GD per tree was calculated for a specific period for as long as at least one tree ring was present in the decade under consideration. However, and to avoid possible bias related to incomplete age intervals and potentially missed GDs, we also calculated the mean number of GDs per tree and decade by only considering those trees for which we had all rings of a specific decade.

In the same way, the occurrence of particular GDs across the lifespan of a tree was then evaluated, with the idea of identifying changing sensitivities of trees to specific disturbances. The presence of scars, compression wood, abrupt growth suppression and abrupt growth increase was studied for all tree species. TRDs were analysed only for *Larix* and *Picea,* as *Pinus* does not normally form tangential rows of traumatic resin ducts due to a different genetic setup of the species (Bannan, 1936; Stoffel, 2008).

Instead, we incorporated growth eccentricity as an additional GD pointing on the debris flow impact in *Pinus* species, as growth eccentricity was considered a reliable signal in older trees where compression wood tends to be much less frequently formed (Šilhán and Stoffel, 2015, Table 2). However, as *Pinus* trees tend to grow towards light, with obvious consequences on tree stability and eccentricity issues (Stoffel et al., 2008), we deliberately limited the weight attributed to growth eccentricity in the intensity classification given in Table 3.

Using the NCSS statistical software, we applied the Kruskal–Wallis one-way ANOVA and *post-hoc* Dunn's test (Dunn, 1961) for the identification of significant differences among the occurrence of GD types across the lifespan of a tree. In addition, the data was analysed further with descriptive statistical tools (such as measures of shape – coefficients of skewness and kurtosis) so as to compare the distribution of GD types across the lifespan of a tree.

In a third step we then focused on reaction intensities following the proposal of Stoffel and Corona (2014; Tables 2 and 3). Comparison was made between the number of unequivocal signals (Intensity 5, 4, and 3) and uncertain signals (Intensity 2 and 1) across the tree lifespan. In addition, we created a category "0" which comprises rather weak growth increase and weak growth suppression as these GDs were previously used in debris-flow histories (e.g. Kogelnig-Mayer et al., 2011), even if Stoffel and Corona (2014) do not recommend to take them into account when it comes to event detection. Intensity categories for growth eccentricity were added as well because they have not been used before. We employed the classical approach of tree-ring eccentricity detection e (Braam et al., 1987) and distinguish three intensity categories based on e ratio changes (Šilhán and Stoffel, 2015, Table 2). The non-parametric Mann–Whitney U test was thereafter used to compare differences among the occurrence of unequivocal and uncertain signals across the lifespan of a tree (the significance level $\alpha = 0.05$).

In a final step, we selected three study sites – (i) Wildibach, (ii) Bruchji, and (iii) Illgraben – for which one tree species clearly dominates the site, i.e. (i) *L. decidua*, (ii) *P. abies*, and (iii) *P. sylvestris*. We focused on specific high-magnitude debris flows at these sites known from archival records for which we know that they have had a strong impact on vegetation (as was also obvious from the abundance of GDs present in the tree-ring series). For these cases, the distribution of GDs across the lifespan of the tree as well as the distribution of intensity categories was then compared with the overall results from all sites.

3. Results

3.1. Data statistics – tree age, number, type and, intensity of GDs

Increment cores from 1539 trees were used for the data reanalysis (611 individuals of *L. decidua*, 422 individuals of *P. abies*, and 506 individuals of *P. sylvestris*; Table 4). Mean age of sampled trees was 178.4 (±89.3) years for the *L. decidua* trees, 119.8 (±53.9) years for *P. abies*, and 121.8 (±40.0) years for *P. sylvestris*. Analyses were performed for 25 intervals in *L. decidua* (between age 11 and 270), 14 intervals in *P. abies* (between age 11 and 160) and 15 intervals in *P. sylvestris* (between age 11 and 170).

The database included 7456 GDs in total (Table 5). The mean number of GD per tree reached 6.9 in *L. decidua*, 4.4 in *P. abies*, and 2.7 in *P. sylvestris*. TRDs were by far the most frequent GD in *L. decidua* and *P. abies* with 68.2% and 56.8% of all GDs, respectively, followed by abrupt growth suppressions (13.0% and 14.7%, respectively). Abrupt growth suppressions and increases dominated in *P. sylvestris* with 44% and 26.7%, respectively. The largest proportion of GDs was attributed to intensity category 1 for *L. decidua* and *P. abies* with 46.8% and 27.2%, respectively, followed by intensity category 4 with 20.8% and 26.8%, respectively. *P. sylvestris* trees mostly responded by GD intensity 0 (38.2%) and intensity 3 (21.2%; Table 6). For the particular types of GDs belonging to each intensity category please refer to Table 3.

3.2. Distribution of GDs across the lifespan of tree

Fig. 2 provides a comparison of the mean number of GDs per time interval and tree; we observe that figures are quite comparable between *L. decidua* and *P. abies* with 0.41 and 0.40 GDs per decade and tree, respectively. *P. sylvestris*, by contrast, showed generally lower numbers of GDs with 0.23 GDs per decade and tree. The evolution of GD abundance across the lifespan of a tree is quite similar for all species (Fig. 2). Above-average numbers of GDs are observed to start when the trees are in their 30s, and culminate in the 6th decade in *L. decidua* trees (0.62 GD per tree), 5th decade in

Table 2
Proposal for the definition of intensities of GDs based on their appearance and/or persistence in the tree-ring series according to Stoffel and Corona (2014). Note that growth eccentricity was added to the overview so as to account for disturbance signals of debris flows in *Pinus* trees.

Type of growth disturbance	Parameter	Weak GD	Moderate GD	Strong GD
injuries and callus tissue	___	___	___	clear indicator of an event
TRD	___	tangentially aligned row with clear gaps between ducts	compact, but not fully continuous rows	extremely compact and fully continuous rows
reaction wood	percentage of compression wood within tree ring	>50% of ring width consists of compression wood cells		
	duration	≥3 years	3–8 years	>8 years
growth suppression	change in ring width (%)	>60%	>100%	>200%
	duration	≥4 years	4–7 years	≥8 years
growth increase	change in ring width (%)	>50%	>100%	>150%
	duration	≥4 years	4–7 years	>8 years
growth eccentricity	ratio e	0.25–0.3	0.3–0.5	>0.5
	duration	≥4 years		

Table 3
Proposal for the weighting of reactions in trees according to Stoffel and Corona (2014).

Intensity	GDs in tree-ring record
Intensity 5	impact scar, strong TRDs
Intensity 4	moderate TRDs, strong reaction wood, strong growth suppression
Intensity 3	moderate reaction wood, moderate growth suppression
Intensity 2	strong growth increase, weak reaction wood, strong growth eccentricity
Intensity 1	weak TRDs, moderate growth increase, moderate growth eccentricity
Intensity 0	weak growth suppression, weak growth increase, weak growth eccentricity

Table 4
Overview of the number of analysed trees and number of analysed GDs from each study site.

Locality	Number of trees				Number of GDs				Sampling year
	all trees	*Larix*	*Pinus*	*Picea*	all GDs	*Larix*	*Pinus*	*Picea*	
Wildibach	344	337	0	7	2891	2842	0	49	2006
Fallzug	29	28	0	1	206	204	0	2	2008
Bielzug	17	16	0	1	216	208	0	8	2007
Grosse Grabe	85	39	0	46	461	200	0	257	2005
Ganterbach	23	0	6	17	71	0	13	58	2009
Bruchji	135	22	0	113	712	96	0	616	2001
Meretschibach	48	0	0	48	176	0	0	176	2008
Illgraben	381	24	352	5	1194	127	1037	30	2006
Lourtier	98	15	0	83	280	49	0	231	2007
Torrent de la Fouly	46	8	0	38	183	37	0	146	2003
Reuse de Saleinaz	174	117	29	28	660	461	61	138	2003
Saint Barthélémy	130	0	119	11	291	0	240	51	2009
Pragser Wildsee	29	5	0	24	119	22	0	97	2010
Total	**1539**	**611**	**506**	**422**	**7456**	**4246**	**1351**	**1859**	

Table 5
Number and proportion of analysed types of GDs identified for each of the three tree species analysed (IN = injuries, TRD = tangential rows of traumatic resin ducts, CW = compression wood, GS = growth suppression, GI = growth increase, EC = growth eccentricity).

Type of growth disturbance	Amount and proportion					
	Larix		*Picea*		*Pinus*	
IN	102	2.40%	86	4.63%	83	6.14%
TRD	2894	68.16%	1055	56.75%	no	no
CW	375	8.83%	241	12.96%	270	19.99%
GS	552	13.00%	274	14.74%	595	44.04%
GI	323	7.61%	203	10.92%	361	26.72%
EC	no	no	no	no	42	3.11%
Total	4246	100.00%	1859	100.00%	1351	100.00%

Table 6
Number and proportion of growth disturbances based on assignment to different categories of intensity reaction.

Category of intensity	Amount and proportion					
	Larix		*Picea*		*Pinus*	
Intensity 5	488	11.49%	297	15.98%	83	6.14%
Intensity 4	883	20.80%	496	26.68%	57	4.22%
Intensity 3	342	8.05%	203	10.92%	286	21.17%
Intensity 2	128	3.01%	140	7.53%	217	16.06%
Intensity 1	1988	46.82%	505	27.17%	192	14.21%
Intensity 0	417	9.82%	218	11.73%	516	38.20%
Total	4246	100.00%	1859	100.00%	1351	100.00%

P. abies (0.53 GD per tree) and during the 3rd decade in *P. sylvestris* (0.35 GD per tree). In a similar way, all species showed below-average numbers of GDs in the 2nd decade as well as after 11 decades. The largest deviation between numbers of GD per tree are observed between the datasets containing partial (solid line in Fig. 2) or full decades (dashed line in Fig. 2), especially during the 2nd decade.

In addition, we observe changes in the occurrence of particular GD types across the lifespan of trees (Fig. 3). By way of example, the most frequent occurrence of compression wood and injuries was observed at rather young median ages of 39–52 years in *L. decidua* and *P. abies* as compared to other types of GD (Table 7). Both types of GDs also exhibit statistically similar medians of occurrences based on Dunn's post-hoc test in all tree species. By contrast, the occurrence of TRDs and abrupt growth increases are much more scattered in *L. decidua* and *P. abies*. Medians of both types range from 69 to 91 years and are thus significantly higher than those of compression wood and injuries. Moreover, the occurrence of abrupt growth increases revealed a platykurtic distribution.

Interestingly, *P. sylvestris* trees showed the most balanced occurrence and distribution of GDs across the lifespan of individual trees (Fig. 3; Table 7). Here, medians of compression wood, injuries, and growth eccentricity are statistically similar. The same observation applies to the medians of growth eccentricity and abrupt growth increases. By contrast, abrupt growth suppressions generally occur at more advanced ages (median = 70 years) than the other types of GDs for which the median was between 44 and 58 years.

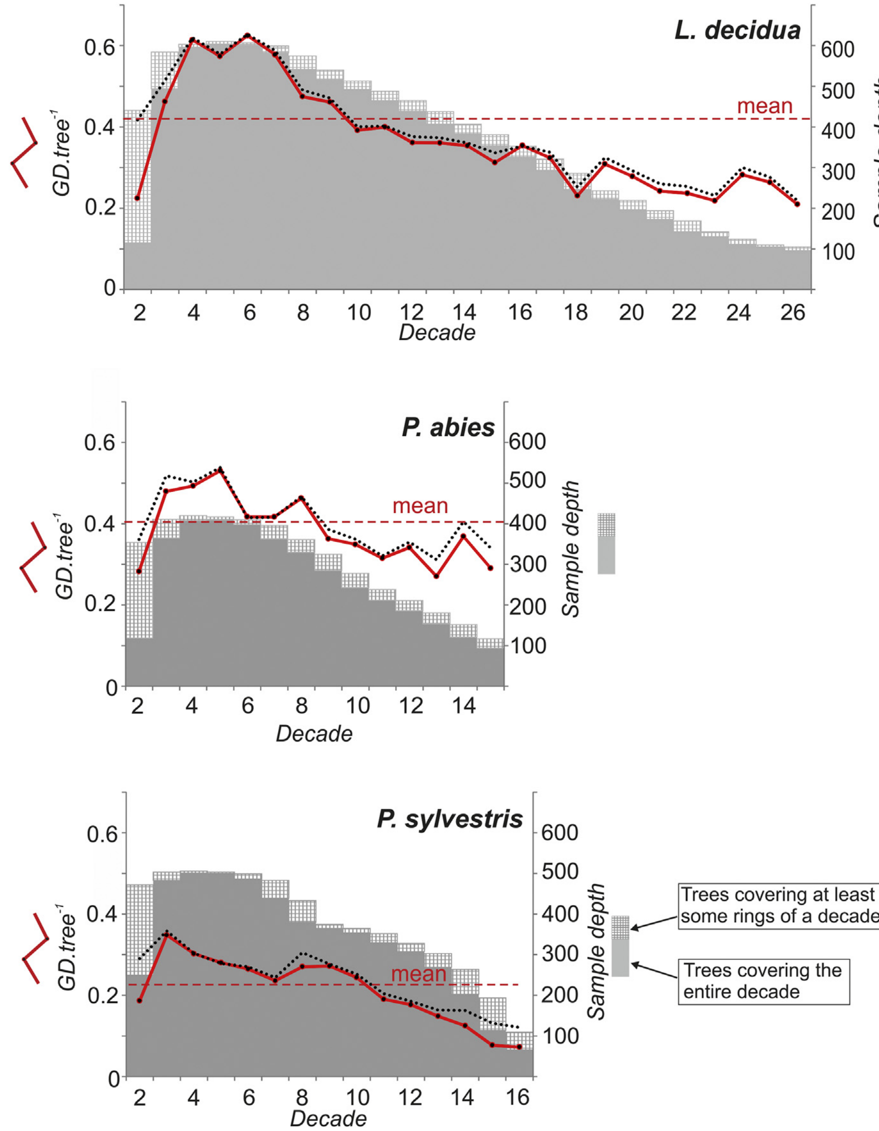

Fig. 2. Temporal distribution of growth disturbances in individual tree and per decade across their lifespan. Data are provided for *L. decidua*, *P. abies*, and *P. sylvestris*. The solid line shows the number of GD per trees and decade for those samples which cover a decade at least partly; the dashed line shows the number of GD per trees covering the entire decade.

In terms of intensity categories of GDs, statistical tests confirm that unequivocal signals (i.e. intensity categories 5, 4, and 3 according to Table 3) generally occur at younger tree age than the more uncertain signals (intensity 2, 1, and 0). The observation is true for all tree species used in this study – *L. decidua*: $p < 0.00001$; *P. abies*: $p = 0.00001$; *P. sylvestris*: $p = 0.0004$ (Fig. 4). We also observe that below-average values of unequivocal signals start to occur after the 10th and 12th decade in *P. abies* and *L. decidua*, respectively (Fig. 5). *P. sylvestris* exhibits again a different picture as uncertain signals predominate over large proportions of their lifetime and as above-average numbers of unequivocal signals could only be observed during the 2–4th and 6–7th decades. Moreover, reactions in *P. sylvestris* mostly consisted of weak growth increases and suppressions which have been included in the new intensity category 0 after the 11th decade (Fig. 5).

3.3. Tree responses to documented high-magnitude debris flows

In addition to the assessment of tree reactions to debris flows in general, we also documented the amount, nature and intensity of GDs following well-known, documented 20th century debris flows on the Wildibach (dominated by *L. decidua*), Bruchji (*P. abies*), and Illgraben (*P. sylvestris*) cones. Mean ages of tree recording GDs related to 20th century debris-flow events at Wildibach ranged from 92.3 yrs in 1978 to 136.5 yrs in 1932. Although very old trees (i.e. 300–400 yrs old) recorded all of the events as well, we nonetheless observe by far the highest number of GDs in trees which were 31–90 years old at the moment of the event. In addition, we also realize that the number of unequivocal signals strongly decreases after the 7th decade and that signals basically disappear after 21 decades of existence of trees (Fig. 6a).

P. abies is the dominating tree species on the debris-flow cone of the Bruchji torrent; here, lower mean ages of GD occurrences can be observed with 44.3–87.5 years, with the oldest tree being disturbed by one of the documented debris flows being 163 years old at the time of the event. The largest number of GDs occurred in trees of up to 100 years in age, whereas the occurrence of GDs became rather sporadic thereafter. The ratio between unequivocal and uncertain signals is generally balanced (Fig. 6b).

P. sylvestris trees growing at the Illgraben showed reactions to

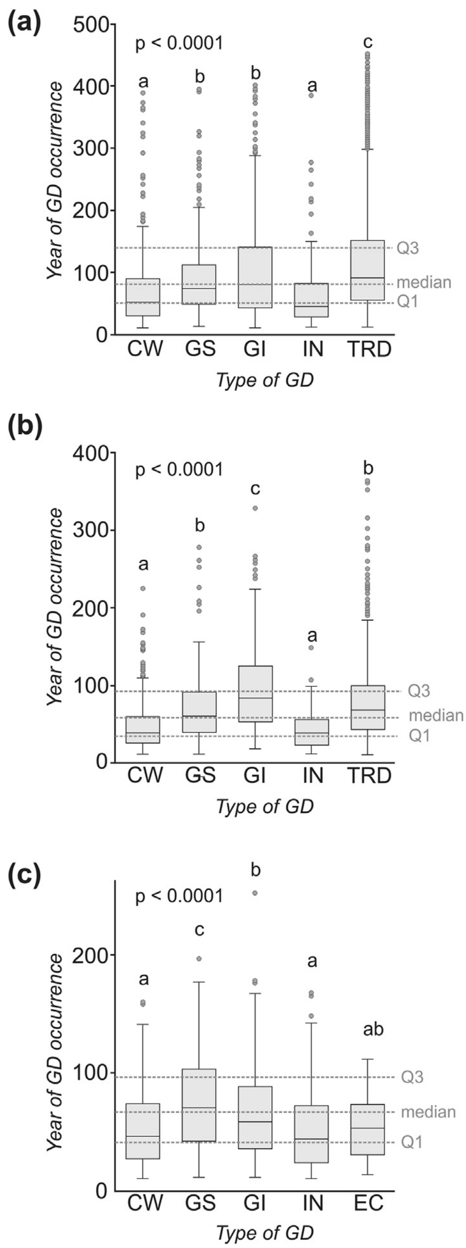

Fig. 3. Box-plots showing the occurrence of particular GD types across the tree lifespan. P-values of Kruskal–Wallis one-way ANOVA test as well as similarities/discrepancies between the occurrences of each pair of GD type based on the post-hoc Dunn's test are illustrated in the graphs.

events mostly between the 7th and 13th decades of their life; the mean age of GDs at the moment of event occurrence in fact ranges from 67.9 years for the 1932 and 114 years for the 1988 debris flow. Uncertain signals prevail for most periods covered by trees expect for the 2nd, 3rd, 4th, and 7th decades of their life (Fig. 6c).

4. Discussion

The occurrence and distribution of GDs was assessed across the lifespan of three different tree species (*Larix*, *Picea*, and *Pinus*) so as to study their ability to record impacts of debris flows at different age stages, as well as to detect changes in their sensitivity to record disturbance events. Through a detailed analysis of 1539 trees containing 7456 GDs, we report differences in the number, types, and intensities of GDs and make recommendations on how to take the increasing age of sampled trees into account in dendrogeomorphic reconstructions.

Table 7
Descriptive statistic variables showing different occurrence frequencies and distributions of GDs across the lifespan of trees.

Growth disturbance	Distribution boundaries			Coefficient of shape	
	min	max	median	skewness	kurtosis
LARIX					
Injury	12	385	45	2.39	6.86
TRD	12	451	91	1.47	1.86
Compression wood	11	389	52	2.49	7.44
Growth suppression	13	394	74	1.73	4.47
Growth increase	11	401	80	1.43	1.68
PICEA					
Injury	12	149	39	1.29	2.54
TRD	11	363	69	1.69	4.7
Compression wood	12	225	39	2.13	5.93
Growth suppression	12	278	61	1.69	4.37
Growth increase	18	328	84	1.21	1.48
PINUS					
Injury	11	166	44	1.28	1.6
Compression wood	11	159	47	0.88	0.5
Growth suppression	12	195	70	0.35	−0.78
Growth increase	12	250	58	1.06	1.79
Growth eccentricity	14	111	53	0.34	−0.96

4.1. Factors affecting age-dependent sensitivity

General agreement exists in tree-ring sciences that the form and abundance of GD will depend on the nature and intensity of the impact as well as on tree heredity and senescence (Stoffel and Corona, 2014). Age-dependent tree sensitivity was thereby often believed to be the driver decreasing occurrence of compression wood in older *Pinus* trees affected by repeat landslide activity (Šilhán and Stoffel, 2015). In a similar way, Šilhán et al. (2015) underlined that the relative occurrence of wounds, compression wood, growth increase, and growth suppression varied substantially between “young” and “old” *P. nigra* trees growing on debris-flow cones in the Crimean Mountains. In their study, however, despite of the large amount of sampled trees (566), results may have been biased by the fact that one single region has been analysed and therefore by its potentially strong influence on event frequencies at this specific locality. Our research, by contrast, included 13 sites and 3 tree species across the European Alps, such that at least 4 different sites were analysed per tree species, rendering results more reliable and less dependent on locally occurring event frequencies.

From our data, it is obvious that all tree species are more likely to record GD at younger age and while they are between 31 and 60 years old, which in fact nicely coincides with results of previous work (Trappmann et al., 2013; Stoffel and Corona, 2014; Šilhán et al., 2015). The lower sensitivity of *P. sylvestris* to debris-flow impact, as compared to *L. decidua* and *P. abies*, can be explained by the thicker bark that partially prevents the formation of wood-penetrating tree wounds (Stoffel et al., 2008). The thick bark of *Pinus* species has indeed been shown multiple times to protect the tree against mechanical impacts, such as hailing (Hohl et al., 2002) or wildfires (Christopoulou et al., 2013). Moreover, as *Pinus* species do not produce TRDs, dendrogeomorphic approaches continue to face some difficulties in identifying debris-flow events (or signs of any other process) in tree-ring series. Consequently, in *Pinus*, the number of GD did not differ significantly across its lifespan due to

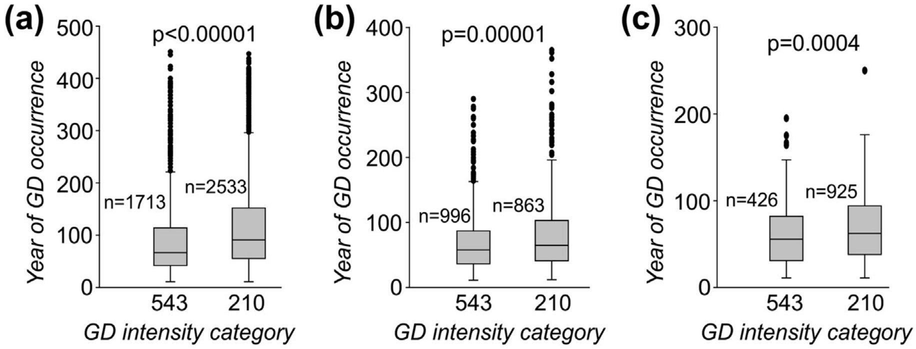

Fig. 4. Boxplots comparing the distribution of unequivocal (intensity classes 5, 4, and 3; indicated as 543 in the legend) and uncertain signals (intensity classes 2, 1, and 0; given as 210 in the legend) across the lifespan of a tree and for (a) *L. decidua*, (b) *P. abies*, (c) *P. sylvestris*.

the absence of TRDs and the smaller number of scars, two features which are typical in young (er) individuals of the tree species studied in this paper.

General agreement also exists on the fact that a thinner bark and a more flexible tree stem will facilitate the recording of mass movement impact (Stoffel et al., 2005b) which in turn results in an abundance of scars and compression wood in younger trees as shown in Fig. 3. By contrast, older trees tend to be more protected by thicker bark structure. In addition, and as a result of important root anchorage and larger mass, older trees will also less likely be affected by stem tilting. However, the older the tree, the more fragile its wood, a fact which, in combination with reduced vitality, may lead to tree death in the aftermath of devastating debris flows.

Interestingly, the youngest trees analysed, being between 11 and 20 year old, did not show very high sensitivity to debris-flow events. This observation is somewhat in contradiction with data from debris-flow sites in mid-mountain reliefs where the impacts of much smaller, and finer grained debris flows on trees has been analysed (Tichavský and Šilhán, 2016). In the case of the sites analysed in this study, young trees affected by debris flows are unlikely to survive, either because of the large forces and boulders involved in impact, due to the poor anchorage of the tree stem and the important sedimentation which is often associated with debris-flow events. Therefore, and in case that debris flows affect the same portion of a cone repeatedly, chances are high that most trees will be killed by the event and that only those trees located outside the affected surfaces will survive and, hence, not show any disturbances in their early days. Such patterns are, in fact, quite well known and used by e.g., Swanson (1988) to derive the history of geomorphic processes by assessing the distribution and/or composition of the growing vegetation.

Our data also show how the distribution of particular GD types changes across the lifespan of a tree. We observe that the loss of flexibility with increasing age will result in an ever increasing scarcity of compression wood. Similarly, wounding of trees is less frequently observed in older trees, which may again be related to bark thickening. By contrast, the presence of TRDs, which is related to the mechanical wounding of trees, could be observed throughout the lifespan of trees. Anatomical studies of wounds and adjacent tissues points to the fact that mechanical impact or pressure as well as the propagation of shock waves in the stem can lead to local cambium disrupture (i.e. to a dis-functioning of the system in charge of dividing cells for wood and bark cell production; Stoffel and Klinkmüller, 2013; Arbellay et al., 2014a, b) and thus TRD formation even in the absence of clearly visible, wood-penetrating wounds (Stoffel and Hitz, 2008; Bollschweiler et al., 2008b; Schneuwly et al., 2009a, b). This means that the conifer trees studied here may well remain affected by the impact of debris flows, even if the debris transported by the events may not abrade the thick bark. Abrupt growth changes (i.e. suppressions and/or increases) were identified frequently in the analysed trees, even in those samples which were more than 100 years old at the time of wounding. However, the reliability is strongly influenced – and sometimes hampered – by the decreasing intensity of the signal which is recorded in the tree-ring series. Growth eccentricity has been used primarily as an evidence for landslide movement, sometimes even in *Pinus* trees (Bollati et al., 2012; Kiszka, 2016). The use of growth eccentricity induced by debris flows has not been applied widely yet; this signal should thus only be used to support more reliable signals but not (yet) as primary signals of debris-flow activity.

The other main observation arising from our results is that unequivocal signals (GDs being evaluated as intensity category 5, 4, or 3 reactions) tend to occur generally in younger trees, whereas more uncertain signals (GDs of intensity categories 2, 1, and 0) are more frequently seen in older trees. By way of example, *L. decidua* tends to produce the largest amount of weaker signals as soon as trees are 100 years or older. Nonetheless, and as shown in the case of the Wildibach cone, even these weak signals occurring in 300–400 year old trees are in fact reactions to strong and well-documented debris flows (see Fig. 6a). In the case of *P. abies*, we observe a mostly balanced ratio between unequivocal and uncertain signals to ages of up to 130 years, which means that this species is able to record events with both strong and weak signals, such that the systematic inclusion of weaker signals – which can also introduce noise to the reconstruction (Stoffel et al., 2013) – seems to be less crucial in this case. As older *P. abies* trees are scarce in our dataset (and in general), it seems difficult to make any statement on how the sensitivity of *P. abies* to debris flows will change in 200 or 300 year old samples. What we can assume, however, is that high mortality can be in *P. abies* affected by multiple wounding as the species is quite susceptible to fungal elicitation (Metzler et al., 2012). By contrast, the abundance of weak (and thus uncertain) signals and the insufficient amount of strong signals in *P. sylvestris* calls for a more flexible approach when compared to *Larix* and *Picea*. Limitations are not only related to the absence of TRDs and the very limited number of wounds, but also due to quite strong uncertainties in the response of trees to stem burial. As *P. sylvestris* usually occupies the driest and harshest environments – often related to calcareous sites where the deposition of fine sediments can act as a fertilizer (Kogelnig-Mayer et al., 2011), the occurrence of debris flows can lead to growth suppressions or increases or to neutral reactions (Strunk, 1997; Stoffel et al., 2008).

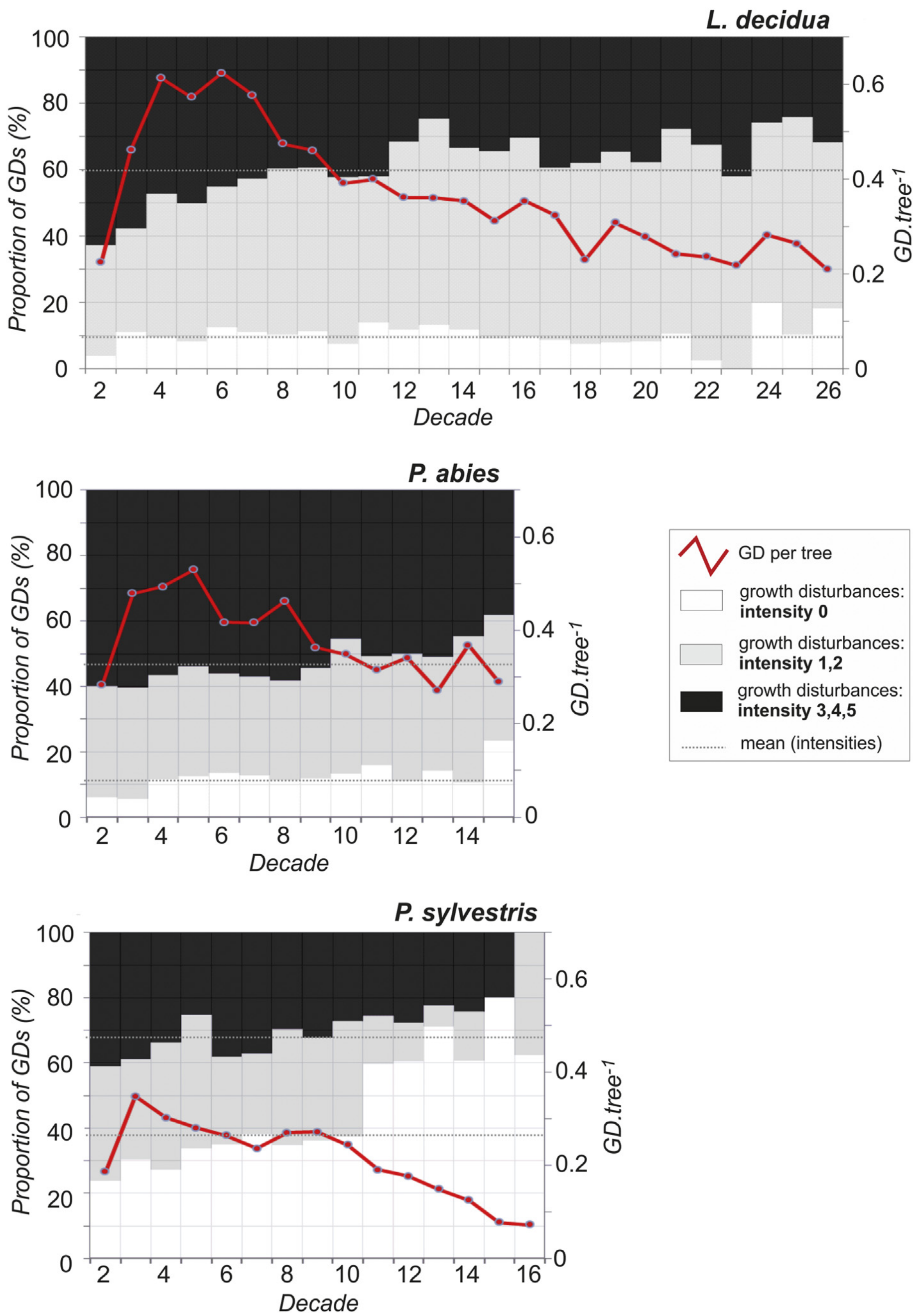

Fig. 5. Distribution of intensity categories of GDs across the lifespan of trees for *L. decidua*, *P. abies*, and *P. sylvestris*.

4.2. Implications of ageing effect on sampling strategy

In the past, many studies have recommended the sampling of trees belonging to different age classes so as to avoid the uncertainties resulting from changing sensitivities of trees to mechanical impacts induced by mass movements (Stoffel and Corona, 2014; Šilhán and Stoffel, 2015). It is obvious that young trees will provide the best records of recent events and with high accuracy, whereas old trees will extend the chronology of debris flows back into the past (Fig. 7a). A study based exclusively on young trees will thus yield quite accurate results in terms of event frequency for the recent past; however, length of the reconstructed time series would suffer clearly from the absence of older trees (Fig. 7b). In the case that a site will be covered predominantly by a very old forest stand, the frequency of the more recent events will likely remain incomplete as a result of decreasing sensitivity of trees with increasing age. However, the chronology would reasonably cover older debris flow events at the site (Fig. 7c). .

Based on the findings of this study and with the aim of improving detection of debris flows in trees of varying age, we recommend future work to take account of ageing during field sampling and during laboratory analyses as follow (Table 8):

- Sampling should be focused on both young and old trees (with old meaning here more than 100 years old) so as to obtain sufficiently long event chronologies with high resolution. Sampling of exclusively young forest stands (with ages up to 50 years) should be avoided where possible because of the

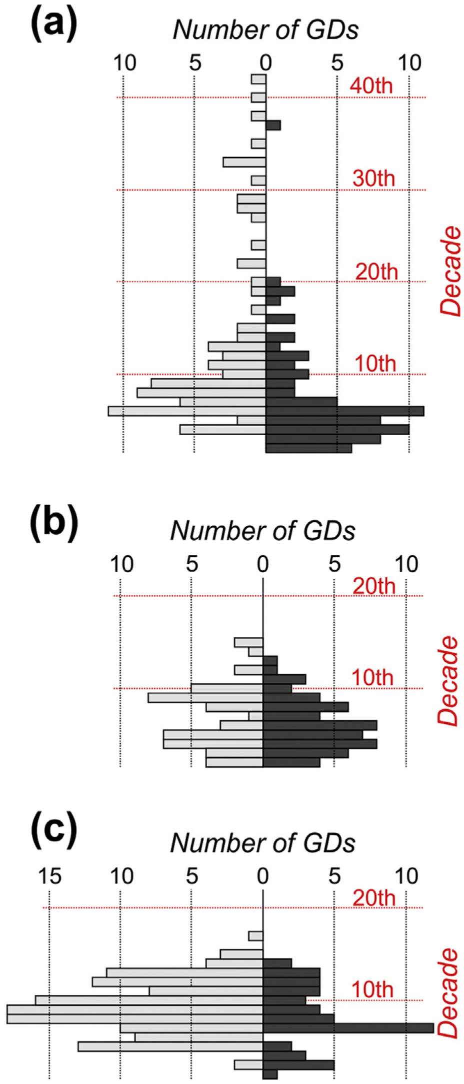

Fig. 6. Distribution of growth disturbances across the lifespan of trees and for selected, well-documented debris-flow events at (a) Wildibach (*L. decidua*), (b) Bruchji (*P. abies*), and (c) Illgraben cones (*P. sylvestris*). Histograms represent the distribution of unequivocal (dark columns) and uncertain signals (light columns) across the lifespan of the trees affected by the events.

generally limited information contained in the tree-ring series. If sampling is limited exclusively on old trees (more than 100 years old) one may consider to sample scarred tree roots if present at the study site to include at least some of the recent channel erosion processes caused by debris flows (Šilhán, 2012; Stoffel et al., 2012; Franco-Ramos et al., 2016; Ballesteros-Cánovas et al., 2017).

- Many of the weak signals identified in this study are indeed reactions to debris-flow activity. In the case of sites with predominantly young trees and strong signals, weak reactions can be neglected, as recommended by Stoffel and Corona (2014). On sites where tree age (almost) systematically exceeds 100 years and where below-average numbers of GDs with predominantly uncertain signals prevail, we suggest to include GDs attributed to intensity classes 2 and 1, especially in the case of *L. decidua* and *P. abies* samples.
- Based on the results of this study, we cannot recommend the construction of debris-flow histories based exclusively on records of *P. sylvestris*. The combination of *P. sylvestris* samples with specimens from other tree species should be preferred to increase the accuracy of results (Arbellay et al., 2010).

5. Conclusions

In this study, we used the largest database of tree-ring series of *L. decidua*, *P. abies*, and *P. sylvestris* from the European Alps to analyse age-dependent sensitivity of trees disturbed by debris flows. The systematic re-analysis of data allowed identification of changes in the occurrence and distribution of GDs in general as well as of particular types of GDs across the lifespan of trees. Based on the findings, we also offer recommendations on how to deal with unequivocal and uncertain signals of past debris-flow impacts and on how to sample forest stands in the future according to the type and age of the forest stand to be investigated.

Our study also offers opportunities to include some uncertain signals in debris-flow reactions, provided that necessary caution is taken, especially in case when reactions are recorded in *L. decidua* and *P. abies* trees which are older than 100 years old. This strategy may ultimately help to refine the precision and quality of debris-flow chronology, but may consequently also lead an increase of noise being considered in reconstructions in cases where signal identification was performed in an inappropriate way. As very old trees may still contain signals of more recent debris flows, yet in the

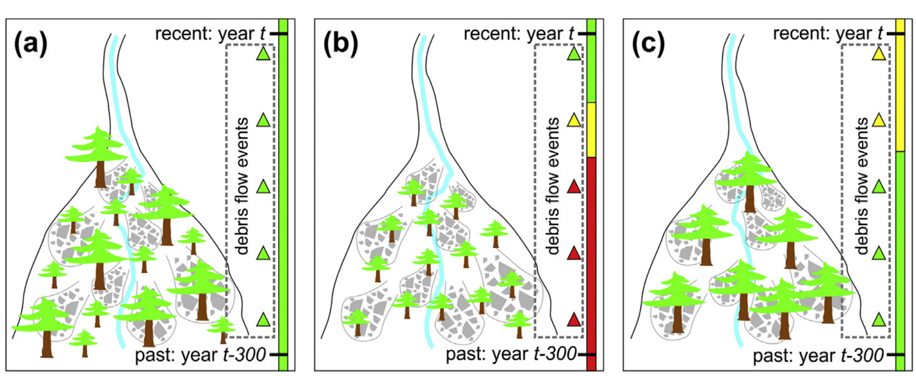

Fig. 7. Assumed reliability of debris-flow chronologies obtained from (a) trees representing various age classes; (b) younger trees reaching ages smaller than 50–70 years; (c) trees being exclusively older than 100 years. The different colour of the triangles are a surrogate for the likelihood of a debris flow to be recorded in the tree-ring series (red – no chance to record the event; yellow – possible to record the event, but difficult to separate signal from noise; green – event recorded). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 8
Intensity of reactions based on Stoffel and Corona (2014). For each intensity category, we provide recommendations on how to proceed with the identification of an event based on different tree species and on different tree age structures in the sampled forest.

Intensity/ Sampling site	Mixed-age forest (*Larix, Picea*)	Mixed-age and old forests (*Pinus*)	Old forest (>100 years old *Larix, Picea*)
Intensity 5 Intensity 4 Intensity 3	unequivocal signals	unequivocal signals	unequivocal signals
Intensity 2 Intensity 1	uncertain signals (only for the reconstruction of spatial pattern of the event which was previously determined by GDs of intensity classes 5, 4, and 3)	not to be used	uncertain signals (these can be considered unequivocal signals of past events in case that they occurred at tree ages larger than 100 years)
Intensity 0	not to be used	not to be used	not to be used

form of weak signals, the inclusion of weak signals should aim at refining or complementing chronologies (also in terms of spatial patterns), and less so in the sense of increasing the number of reconstructed events. At the same time, and wherever possible, the results also point to the need of including samples of as many age classes as possible so as to obtain the most reliable reconstruction. Whereas the study sites across the world may not provide the "ideal" age composition of forests due to, for instance, forest management interventions or presence of high-magnitude disasters, the list of recommendations provided here seems to be a good alternative when the conditions are somewhat limited.

As dendrogeomorphic reconstructions are not focused exclusively on the conifers described in this study, there is an urgent call to evaluate the age-dependent sensitivity of broadleaved trees as well so as to complement the recommendation provided here. Furthermore, a better understanding of the least reliable growth disturbances in dendrogeomorphology (i.e. growth suppressions and increases) would clarify their use in spatio-temporal reconstructions of geomorphic processes. We therefore also call for experimental studies dealing with the burial of stem bases and subsequent detailed analyses of responses in the tree-ring series, even at the level of tree-ring anatomy.

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